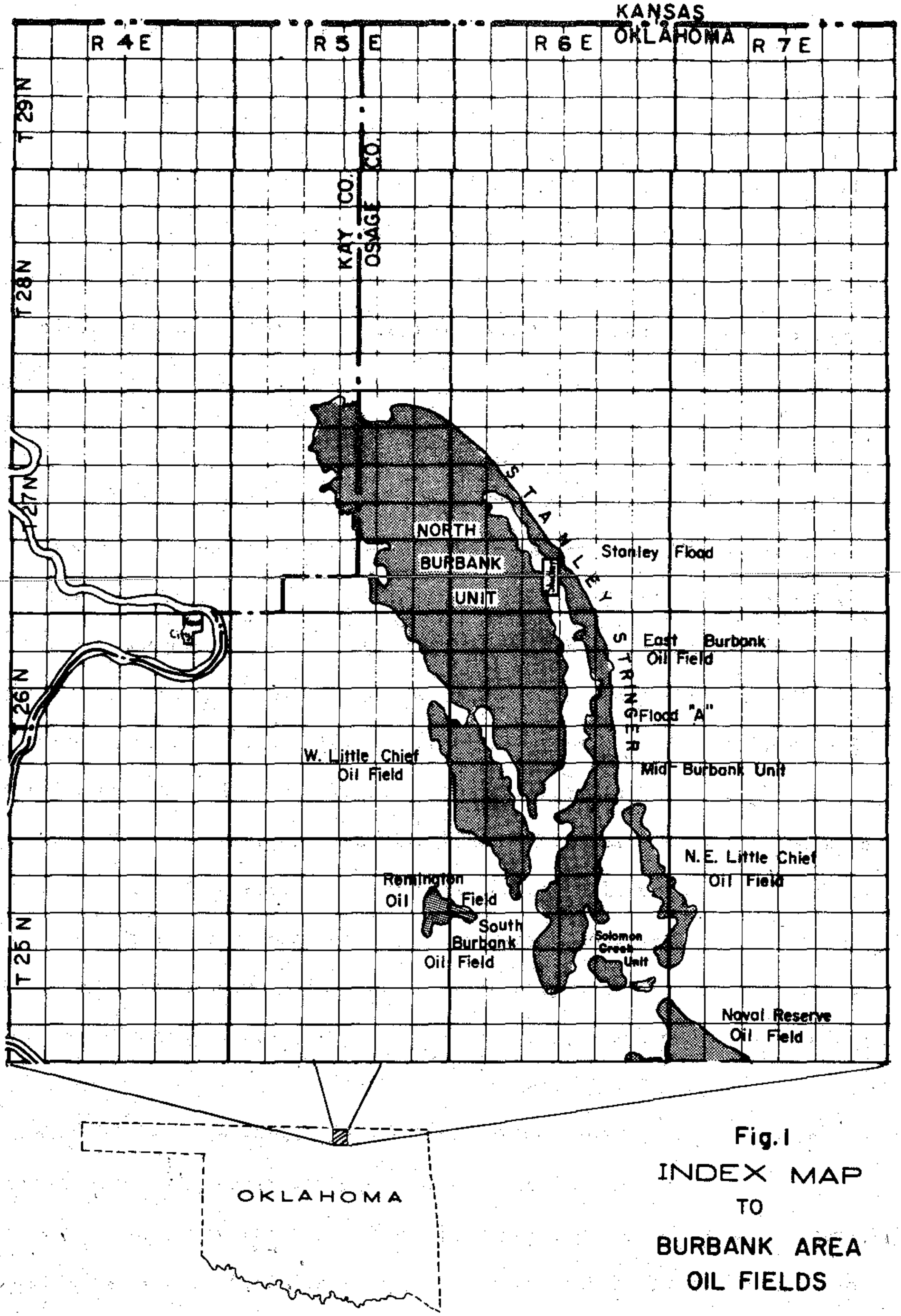


Fig. 1
INDEX MAP
TO
BURBANK AREA
OIL FIELDS

HISTORY OF THE BURBANK FIELD

In order to understand the "why" about waterflood problems at North Burbank Unit, it is first necessary to know the history of the development of the field. Troubles resulted from a set of reservoir conditions, both natural and imposed, starting shortly after discovery of the pool.

Discovery

North Burbank field was discovered by the Marland Oil Company in May 1920. The discovery well was located on a surface anticline (Plate II - SE$\frac{1}{4}$, NE$\frac{1}{4}$, sec. 36, T. 27 N., R. 5 E.) which had been favorably recommended by the geological survey in K. C. Heald's report of 1916. In September 1920 the Carter Oil Company completed two wells on a dome located three miles to the southeast in sec. 9, T. 26 N., R. 6 E. Thereafter, the field developed rapidly; sometimes all 16 wells in a particular tract were drilled simultaneously. Wells were drilled with cable tools, of course, and were produced to fullest capacity by open flow and swabbing or pumping when necessary. Most wells were shot with heavy charges either at completion or shortly thereafter when they stopped flowing (Hunter, 1956). A common misconception of those early days was the belief that: "rapid development of a field with subsequent open flow from the wells where the producing sand is close grained produces a much larger ultimate production" (Sands, 1924).

Peak production of 122,000 bbls per day was achieved in July 1923, just three years after discovery. There was little knowledge of modern conservation methods and so it is not surprising that production declined rapidly as a result of the wide open operation. By 1924, most wells had to be put on vacuum in an effort to maintain production. Gas repressuring was started in some sections in 1926 and continued for over 30 years on fringe properties not under waterflood.

Also in 1926, the Stanley Stringer was discovered. As its name implies, it is a long narrow sand body which merges with the main Burbank field at its northeast corner (Fig. 1). Development of the Stanley Stringer was sporadic due to the narrowness and unpredictability of the producing sand. Complete development was not accomplished until the late thirties. It is parallel with and separated from North Burbank field by an equally narrow zone where the Burbank sand is missing, replaced by shale. The geometry of the Stanley Stringer and Burbank field suggest they were formed as beach and bar deposits of the Pennsylvanian Cherokee sea (Bass et al, 1937, 1952, Plate III); however, some authors are able to present evidence that the entire complex is fluvial in origin (Hudson, 1970). This issue will remain undecided for the purpose of this thesis. In general, the reservoir sand body may be pictured as being encapsulated in shale forming a stratigraphic trap for the hydrocarbons.

Nature of the Reservoir

The North Burbank field, as finally developed, trends generally north-northwest. It is 12 miles long, 4 to 5 miles wide and includes some 23,000 productive acres. The producing horizon is the Pennsylvanian Burbank Sandstone Member of the Cherokee Shale, found at a depth of about 3000 feet. Maximum thickness of the Burbank sand is 125 feet and the average thickness is 57 feet. It is a fine-grained quartz sand, loosely cemented by magnesium, iron and calcium carbonate, and locally by silica, dolomite or calcite. It contains about one percent mica, traces of feldspar, zircon, chlorite, glauconite, hornblende, rutile, magnetite, pyrite and epidote, 10-20 percent detrital rock fragments (chert, shale and schist) and 10 percent carbonaceous material (Bass et al, 1937). Swelling clays could not be found after numerous tests on cores, a determination of no small significance in diagnosing the waterflood difficulties.

The limits of the field are determined by an abrupt sand to shale lithology change on the east and a tilted oil-water contact in combination with a permeability barrier on the west. Regional strike of bedding is north-south and dip is gentle to the west, averaging only 40 feet per mile. There are several small structural reversals (Plate II) at the southeastern end of the field which are extremely low relief but were large enough to be mapped by plane table methods in 1915. As noted above, the domes recommended by Heald in U.S. Geological Survey Bulletin 641 were the structural leads that resulted in the discovery of the field. However, this is where the significance of local structure ends, because the most prolific production was found in the northwestern part of the field, several miles from the crests of the structural highs and 100 to 150 feet down-dip. Generally speaking there was no gas cap for the field, although the structurally high Marland well and others nearby did produce some gas.

Hunter (1956) stated that a portion of the field, lying in Kay County, had natural water drive from Mississippian water entering the Burbank sand at a pinchout against the Mississippian lime. Reservoir energy for the field was almost entirely due to dissolved gas in the oil (Hunter, 1956). Original reservoir fluid pressure was estimated to be

1200-1300 psi. Average porosity of the sand was 16.8 percent and permeability ranged extensively, from zero to several darcys, with an average of 100 millidarcies. The north part of the field has considerably higher permeability than the south. Oil gravity is 38°-42° API. Permeability trends based on initial potentials show a broadly arcuate pattern, curving west to southeast in a north to south direction (Bass et al, 1937, Plate III).

Secondary Recovery

With the rapid natural depletion and only limited success with gas repressuring, the 18 operators of the North Burbank field were anxious to inaugurate secondary recovery. Accumulated oil production from the entire North Burbank field, including the portion in Kay County and the Stanley Stringer, had amounted to 221,104,498 barrels by November 1, 1949. The reservoir pressure was practically depleted, reportedly ranging from 0 to 10 psi. (It is doubtful that the pressure could have been quite this low.) Only 17,000,000 additional barrels of oil could be attributed to repressuring. Primary recovery was only 25 percent of the estimated initial oil in place. In 1946, at the request of the Osage Indian Agency, the North Burbank operators met to examine the possibility of increasing production (Hunter, 1956). It was known for some time that the field was an excellent prospect for water flooding. Dissolved gas expansion drive is relatively inefficient, and leaves so much oil in the reservoir that its recovery by waterflooding is often profitable. Negotiations between the North Burbank operators and the Osage Tribe resulted in the issuance of a blanket lease covering 23,900 gross acres effective November 14, 1949 (Fig. 2). This was to be the world's largest waterflood program up to that time. The waterflood

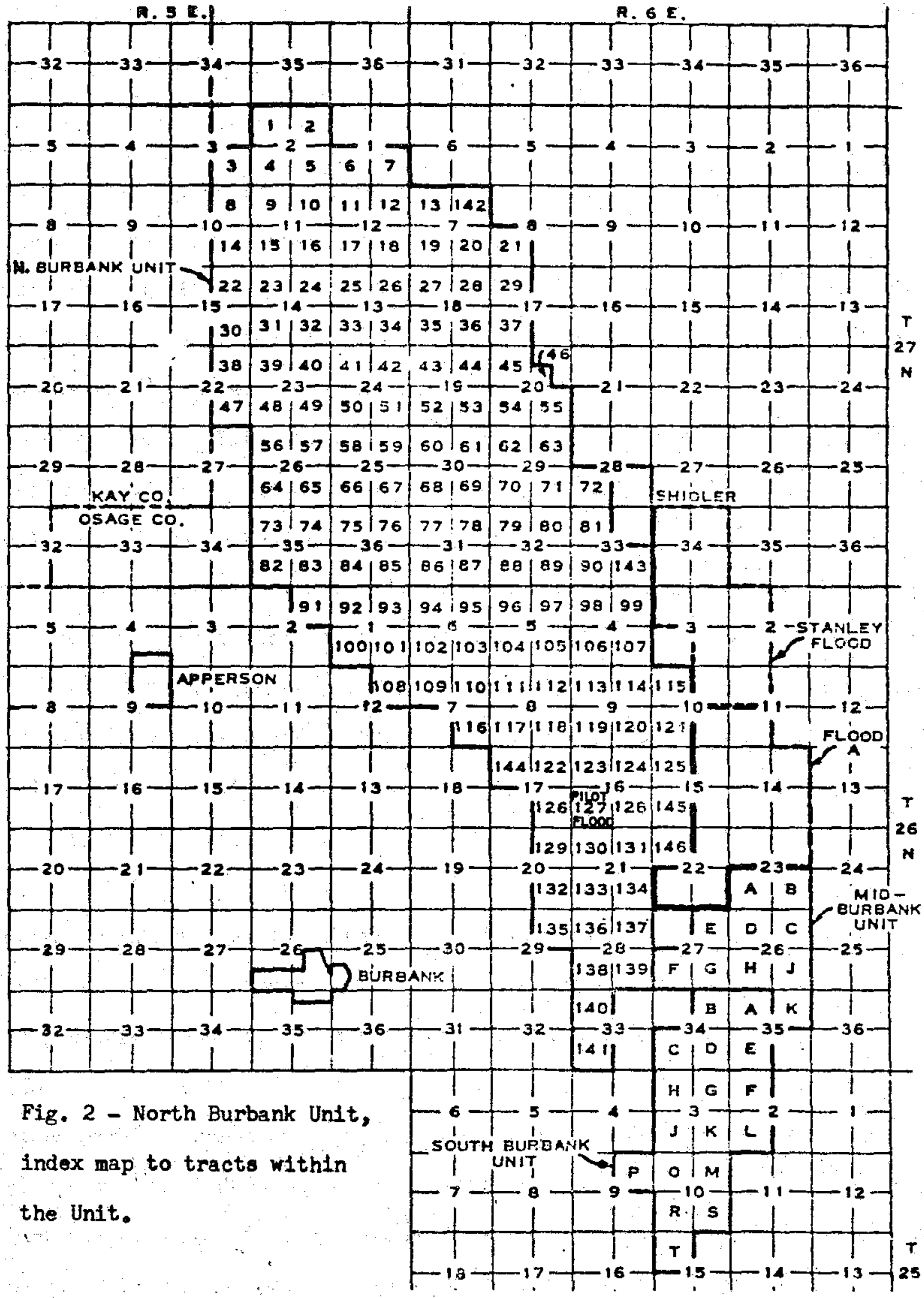


Fig. 2 - North Burbank Unit, index map to tracts within the Unit.

Courtesy of Phillips Petroleum Company

reserve was estimated to be 140 million gross barrels of oil to be recovered over a period of 30 years (Hunter, 1956).

The Pilot Flood

The waterflood program began in March 1950 with a 90 acre pilot flood in tract 127 containing nine 5-spot water injection wells on 10-acre spacing (Figs. 2 & 3). The 5-spot pattern provides for one recovery well surrounded by four injection wells per 10 acres. The close spacing was desired to effect an early answer to the effectiveness of the flood (Hunter, 1956). Eight of the nine injection wells were drilled expressly for this purpose. The ninth well was a converted core test that had been drilled in 1943 to test waterflood reserves. Cores were recovered from the eight newly drilled wells for analysis and were found to be similar in every respect to Bartlesville-Burbank sands that had been successfully flooded elsewhere (Hunter, 1956). Permeability varied considerably in a given well but there was no evidence of permeability channels between wells (T. A. Mathews, oral communication). Remedial work was performed on the recovery wells to insure a good test of the water flood.

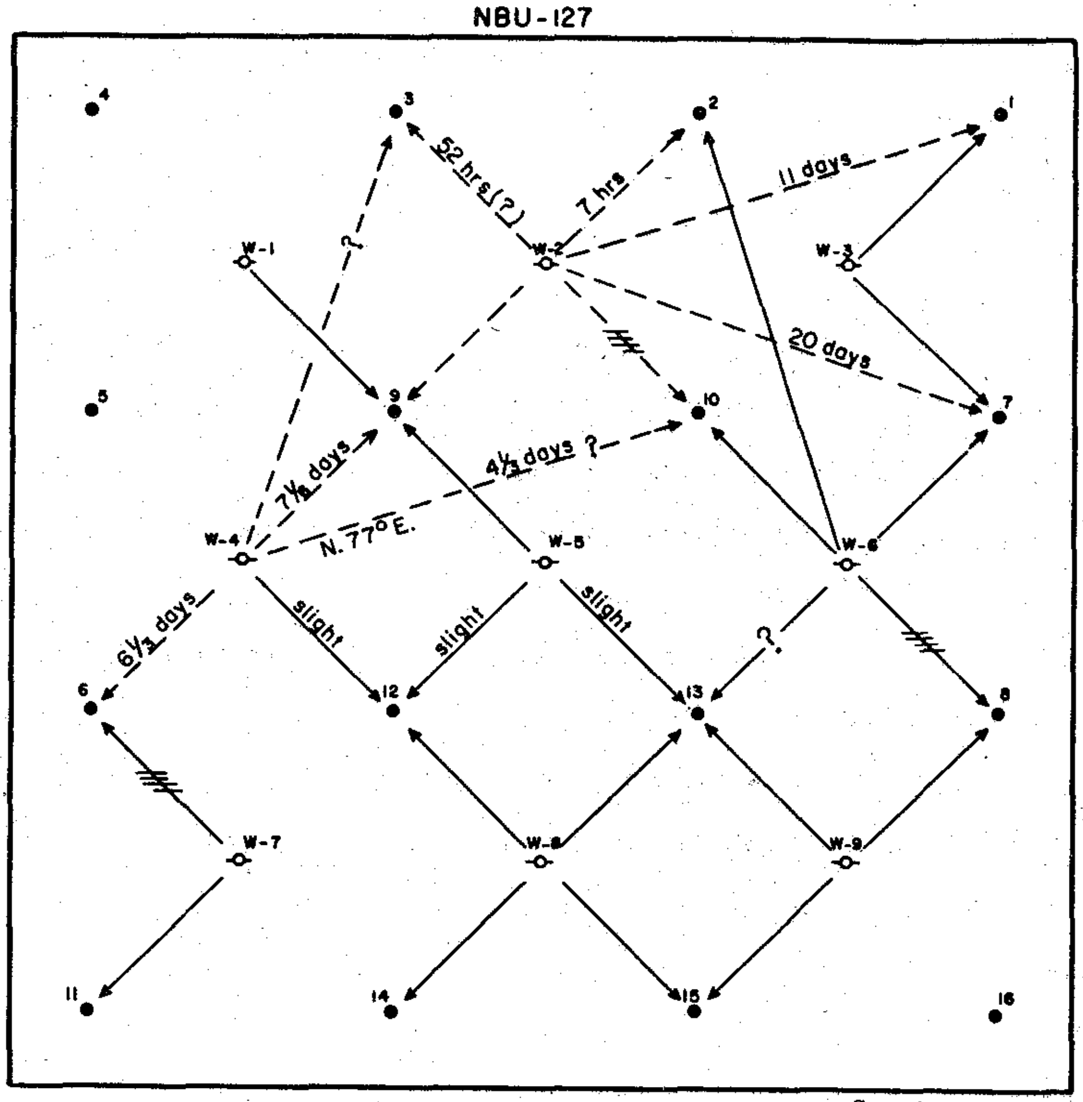
Water for the pilot flood was a combination of salt water, produced by isolated wells in the area, mixed with fresh water from a nearby industrial supply (Hunter, 1956). First water was injected in March 1950 at pressures equal to or less than the hydrostatic head (Hunter, 1956). (This is an important observation concerning the question of whether the reservoir was opened by early overpressuring of the reservoir.) Fill-up volume was reached in September as expected and following fill-up, production for the tract increased from 37 barrels to almost 1000 barrels of oil per day (Hunter, 1956). Peak waterflood production was reached in January 1951. The operators were elated with the success of the pilot flood and work began immediately on a 1000 acre extension.

Early Troubles

The pilot flood was not without its problems; oil production was increased, but water production in some wells increased sharply also.

In December 1950 and January 1951, a series of tests were run in the pilot flood with uranine dye to determine the water travel pattern from input well 127-W-4 and particularly to determine the source of water being produced by well 127-6, which had an abnormal water-oil ratio since its waterflood stimulation in October 1950. The tracer dye tests showed rapid water channeling occurred in various directions, with immediate offset wells being bypassed in some cases. For example, as shown in Fig. 3, dye from W-4 was recovered in 127-6 and -9 in six and one-third days and seven and one-sixth days, respectively. Each of these wells is approximately 475 feet from the injection well. More impressively, tracer dye from W-4 traveled to 127-10, a distance of about 1000 feet in four and one-third days. It was concluded that input water was channeling directly from 127-W-4 to 127-10. Dye was never found in 127-12, and the low dye concentration coupled with excellent flood performance of 127-9 indicated no serious water travel in that direction.

In March 1951, uranine dye was injected into 127-W2 in an effort to determine the source of unusual water production in 127-2, and to determine water travel from 127-W2 (Fig. 3). The results of this test were more dramatic. Dye was observed in a water sample from 127-2 in seven hours after injection. Dye was found in water from 127-3 in 52 hours, in 127-1 in 11 days and in 127-7 in 20 days. No uranine dye was found in samples from 127-10 or from 127-9. It was concluded that input water from 127-W2 channels directly to 127-2 and to somewhat less degree



Courtesy of
Phillips Petroleum
Company

Indicated flow from brine analysis
No flow indicated from brine analysis
Indicated flow from uranine dye tracer tests
Test at W-4 on 12-30-50
Test at W-2 on 3-6-51

Fig. 3 - Plat of tract 127, North Burbank Unit, showing the direction and time of rapid water channeling as determined from brine analysis and tracer dye tests of input waters.

to 127-3. No apparent channel exists between W2 and 127-1, 7, 9 or 10.

From the foregoing evidence, it is considered likely that the joints in the reservoir were open to some extent prior to the waterflood and certainly prior to the injection of water under pressure. Water wasn't injected under pressure until after input rates fell due to reservoir sand face plugging.

Waterflood Extension

The extension program was engineered by converting alternate existing wells to water input, thus producing a 20 acre 5-spot pattern (Hunter, 1956). Converting existing wells to water input involved pulling the old casing and liners and cementing a string of pipe to the top of the Burbank sand. It was recognized that the shale section immediately above the sand was highly fractured, which caused lost circulation problems in drilling wells and certainly would be a thief zone during flooding (Hunter, 1956). The same procedure was used for each additional 1000 acre extension during the years 1952 and 1953; the conversion costing approximately half of the cost of drilling a new well (Hunter, 1956).

Great care was taken in planning the water supply for this giant project. Millions upon millions of barrels would be eventually needed. More than one and one-half billion barrels have been injected over the past twenty years. The Ark-Burbank water system was designed to satisfy the total requirements of all the Burbank fields (Hunter, 1956). Water is obtained from wells located in the Arkansas River valley located seven miles west of the North Burbank Unit. Each of seven wells is capable of producing over 40,000 barrels of water per day from the alluvium fill in the valley (Hunter, 1956). A total of 290,000 barrels per day was the estimated total requirement. The water source was considered to be reliable, even during dry periods, and to be clear of sediment as a result of the natural filtering action of the alluvium (Hunter, 1956).

More Troubles

The initial results of the 1951 extension were as expected. In the quarter section immediately south of the pilot flood normal production jumped from 50 barrels of oil per day to 1100 barrels per day. In the adjacent tract, the production increased from 50 to 900 barrels of oil per day (Hunter, 1956). Fill-up was calculated to occur in March 1952.

> However, within a few months there was a sharp decline in the rate of water injection followed closely by a decline in both oil and water production. This was initially attributed to the problem common in waterfloods, that of water input well plugging (Hunter, 1956).

In November of 1951, it was noted that two wells in tract 127 and one well in tract 126 were being slowly plugged as a result of sulfate-reducing bacteria. In addition, edge injection wells in tracts 126, 129 and 132-1 had much lower permeability than those in the middle of the field. They also contained a larger percentage of clay, probably due to their stratigraphic position at the edge of the sand body. These clays were believed to be swelling when flooded with fresh water. Attempts to remove the input-well plugging followed the usual procedures of back-flowing, acidizing, shooting and application of pressure (Hunter, 1956). Only increased surface pressure proved to be effective. No damage to the reservoir was anticipated at surface pressures up to 1000 psi (Hunter, 1956). In order to test the reservoir, water was injected at 300 psi initially, with a gradual increase to 600 psi. At 300 psi the volume of water taken by the reservoir was well above the expected increase. It was assumed that the increased pressure had successfully removed the barrier formed by plugging material in the sand face. More likely the increased pressure had enlarged the natural joints in the reservoir.

Early Evidence of Natural Joints in the Reservoir

Other evidence is available suggesting the joints were open prior to the waterflood. Mention of a joint system in North Burbank was recorded as early as 1928, when drillers reported while cleaning out NBU 143-1, "The hole was previously filled with mud which got away through a crevice." This report, other similar reports, and the early problems of casing leaks affecting east or west offset wells established that some sort of joint system existed.

In 1945, uncontrolled water bypassing on Bait Unit L, M, O, P and W leases (Plate IV) was believed due in large part to water traveling through the fractured shaly sand section immediately overlying the Burbank sand. This conclusion was based on a loss of 500-600 barrels of drilling mud at Bait O 17 (tract 105-5) while coring jointed shaly sand. In 1949, a boron tracer was injected into salt water disposal well Bait M 13 (106-13). The tracer was found at Bait M 7, 1,300 feet west and 600 feet north, in a matter of hours, but was not found in any of the other active wells in the area.

Direct evidence of joints in the reservoir was obtained in the form of fractured cores recovered from various waterflood test wells drilled before unitization (Fig. 4). In fact, joints of some extent were found in almost every core taken from the Burbank zone. NBU 130-7A, drilled as a recovery well, had cores which were extensively jointed. One joint extended from top to the bottom of the core. The joint was at

Fig. 4 - Fractured core from Kewanee Oil Company Noble 2 well, sec. 23, T. 26 N., R. 6 E. The cored section shows an extensive joint system through the interval 2921 to 2949.6 feet. Coring was started in jointed shale at 2921 feet. Top of the oil sand was encountered at 2932.8 feet. Bottom of the oil sand is at 2956 feet. Note the joints are perpendicular to the bedding and are parallel to the length of the core. In the case of fractures caused by drilling, the fracture plane is centered throughout most of its length and terminates by curving abruptly toward the side of the core, as described by Pendexter and Rohn (1954).

Courtesy of Kewanee Oil Company

Fig. 4

least 1/4 inch wide. Surprisingly the well produced only 34 barrels of oil to 23 barrels of water in one test. Some joints in cores are filled with secondary calcite. However, examination of several of these cores indicates that some fractures may have been induced by drilling. The criteria for differentiating drilling induced fractures from natural fractures in cores have been outlined by Pendexter and Rohn (1954).

Numerous cores display no joints in the reservoir sand but are highly jointed in the overlying and underlying shale-silt intervals (Fig. 4). All wells which penetrated the lower shale interval suffered no lost circulation problems during or after the shale was penetrated, suggesting the bottom shale, even though jointed, was not a water loss zone. Engineering records for the waterflood program cite numerous instances where water was presumed to be lost to fractured shales above the reservoir sand. Records of July 1953 specify 44 wells where circulation was lost in varying amounts. These wells are indicated on the thesis area map (Plate V) and curiously, they are concentrated in a northeast-southwest trending group. Many have a history of other tests for channeling or oriented cores either by design or coincidence. Remedial work usually included squeeze cementing and casing off these fractured intervals.

Uncontrolled Flood of the Stanley Stringer

In February 1952, the operator of the Stanley Stringer noticed water encroachment on the Fronkier lease in Well 3, Flood "A" (Plate IV). "This influx was first noted prior to installation of pumps for pressure injection on North Burbank Unit" (Hunter, 1956). In the next several months, additional wells began to show quantities of water which could not be handled with the existing pumping equipment. In July of 1952, tests were made on suspected wells for casing leaks. The tests indicated that casing leaks did not exist. By September 1952, the following wells were determined to be suffering unreasonable water influx: Fronkier 2, 3, 4; Lawrence 1; Nieman 1, 3; Lewis 1, 2, 8 and 10; and Teke 5 (Plate IV). Water locater surveys using the Dowell photoelectric water locater were run on a number of the wells. It was established that in all cases the water was entering the wells in the upper portion of the section, largely in the sandy shale section which overlies the Burbank sand. By November 1952, the volume of water entering the area had reached such proportions that concern was felt over the possibility that an uncontrolled flood would reduce the chances for a successful future secondary recovery in the area.

Large pumping units were installed to handle the increased volumes of fluids in the flooded wells. Production reached 5000 barrels per day with an 8 to 1 water-oil ratio. Further encroachment of water was noticed northward across the Lewis lease into the Teke lease (Plate IV). Stimulation was also noticed southward into the northern edge of the Mid-Burbank Unit.

In order to determine the source of the water, a large number of water analyses were taken from the various producing wells in Stanley Stringer Flood "A" (Fig. 2). As water production increased in the various wells, it was noted there was a general reduction in chloride content. It was also noted that the barium content in the fluids from these same wells increased, even though barium is foreign to Burbank sand connate water. Iron sulphide was noted in all stimulated wells which had not been so contaminated previous to water encroachment.

After all other sources had been discounted, it was finally determined that the uncontrolled flood must be related to the North Burbank waterflood program. The first encroachment into Flood "A" in February 1952 coincided with the fill-up of NBU's 1951 extension. Sizeable water losses were under study at North Burbank and it had been postulated that the water had entered the highly jointed sandy shale unit overlying the Burbank sand via joints in the sand created by nitroglycerine shot wells. At first it seemed unreasonable for water to enter the Stanley Stringer from North Burbank Unit since the Burbank sand was known to be missing in the interval between the two reservoirs; but, the quantity of water lost as compared to water recovered by wells within the unit as well as in the neighboring fields had to be due to a "thief zone". Over 9,000,000 barrels of water were unaccounted for by July 1955. Since the jointed shale was the only interval present between the waterflood and the Stanley Stringer it had to be the water loss zone.

To further test the assumption that North Burbank waterflood was stimulating the Stanley Stringer, a number of injection wells which had high input rates were shut-in and the recovery of water in affected wells of the Stanley Stringer decreased almost immediately. On July 29, 1953 and August 1, 1953, 19 input wells in tracts 124, 125, 126, 128, 132, 134, 137, 141, 144, and 145 were shut down and by August 1, 1953 the Kewanee wells were affected. Through August 14, a decline of 850 BPD to 680 BPD oil production and 5,400 BPD to 3,200 BPD water production occurred in Kewanee's Flood "A" and Teke leases.

At this time, a Unit well being drilled offered an opportunity to make a drill stem test of the overlying sandy shale. The tests indicated the jointed shale was full of water chemically identical to that of the flood.

Stimulation of West Little Chief

At about this same time, the operators of West Little Chief pool, lying west of the Unit (Fig. 1), reported an encroachment of water from the North Burbank flood. It appeared that water movement outside the unit was quite directional, east to Stanley Stringer and west to Little Chief. Within the unit itself, numerous instances were reported where flood water channeled directly to adjacent east and west oil-producing wells. Yet there were no instances of water channeling to a producing well located north or south of an injection well (Hunter, 1956). All evidence pointed toward a general east-west joint system which was apparently quite lengthy.

Magnetic Orientation of Fractured Cores

An oriented core was taken from a newly drilled well and although it was not openly fractured, when subjected to pressure, it could be ruptured along planes of weakness which were oriented east-west (Hunter, 1956). The east-west joint system was further confirmed by sending seven older fractured cores to Sperry - Sun Laboratories in Long Beach, California to determine orientation of the joint planes by residual magnetism. Although this system of orienting cores is presently discounted, primarily due to the evidence for magnetic reversals, polar wandering, and continental drift, the results of Sperry - Sun's work are strangely accommodating. The orientation of the fractures varied from N. 69° E. to S. 53° E. with a predominant east-west direction. The fracture orientations in all cases except one (well 117 - 8A) agree closely with the known water channels in the immediate vicinity. Core 117 - 8A may have been inverted, which could have caused a faulty determination.

The following shows the results of the Sperry - Sun orientations, and the orientations are also superimposed on the respective wells on the thesis area map (Plate V).

Well No.	Depth-feet	Lithology	Orientation
113 - 6A	2623	shale	N. 63°E.
113 - 6A	2723.5	shale	N. 82°E.
117 - 8A	2886	sand	S. 53°E.
128 - W4A	2888	shaly sand	S. 77°E.
130 - 7A	2961	sand	N. 69°E.
* 130 - 7	2797	shale	-
131 - 16	2946	sand	S. 68°E.

* Strongly vertically magnetized possibly due to a magnetized core barrel.

Another oriented core was taken during the drilling of NBU 130 - 17 test well in 1953. Coring was started at the base of the Oswego Limestone (2745 feet RKB). The core bit was used in conjunction with Eastman's magnetic core orientation collar. Oriented cores were taken at 2799 - 2810 feet, 2810 - 2816, 2860 - 2878, 2922 - 2930, 2958 - 2974 and 2982 - 3000 feet. Three closed vertical fractures were oriented as follows: fossiliferous shale 2816 feet NE - SW, shale 2873.2 feet ENE - WSW, and Skinner sand 2877.8 feet E - W. These directions are plotted on Plate V. The remaining cores had no fractures which could be oriented.

Change to Line Drive Pattern

In 1955, after four years of 20 acre 5-spot pattern, the secondary recovery program was in serious difficulty. It was now concluded that natural and incipient vertical joints were responsible for causing east-west water channels and the resulting low sweep efficiency. Although waterflood recovery had been good, it was estimated that 8,649,000 barrels of recoverable oil would be left in place, based on declining rates. It was considered necessary to make some marked changes in the waterflood pattern to overcome the effect of the directional jointing. It was proposed that the field recovery program be converted to 20 acre line drive, in a north-south direction.

To implement line drive, the input wells were aligned in east-west rows, alternating with rows of recovery wells (Plate V). With this pattern, joints still act as channels; however, the producing formation floods more efficiently due to water entering the reservoir perpendicular to the plane of the joint. The open joints fill with water first and since bottom hole fluid pressures are approximately equal along the east-west row of input wells, the water cannot channel and must move north and south into the reservoir, increasing areal sweep efficiency. Joints in the vicinity of the recovery well may act as gathering lines. Several very pertinent papers have been published on the subject of fracture orientation relative to areal sweep efficiency by: Crawford and Collins (1954); Hansford and Donohue (1967); Donohue (1967); and Fraser and Pettitt (1962).

The foregoing assumes that the joint system is basically unidirectional. Most of the evidence presented suggests that this is the case; however, there is also evidence that the joint system is more complex. Firstly, the surface traces of joints in the outcrop show that several distinct trends exist; and secondly, dye tracer tests on tract 127 show that rapid water channeling occurred in various directions (Fig. 3). This particular observation is not surprising. The Burbank sand is well noted for its lack of uniformity; witness the variable primary production patterns mapped by Bass et al (1952, Plate III). Thus there is no reason to assume that a uniform and unidirectional joint system would exist as will be explained in the section of this text titled: Description of Joints.

Reservoir heterogeneity is further indicated by the wide range in breakdown pressures recorded across the length and breadth of the field. It is reasoned that at or about fill-up, the water in the input wells reaches a pressure sufficient to open up the joints in the reservoir rock and also in the overlying shale. When increased surface pressure was required to overcome plugging, this pressure was sufficient to break apart the formation in many cases. Sometimes breakdown pressures were considerably lower than expected. Pressure input tests show formation breakdown ranges from a low of 295 to a high of slightly over 500 psi (wellhead). Low breakdown pressures along the east side of the Unit, tracts 125 south to 137, suggests that the eastern edge may have a more intensely developed system of joints than the west side. This observation was recently used as the basis for recommending changing the waterflood pattern to an east to west line drive in the northwestern part of the Unit.

The Five Spot Rectangle Pattern

By 1954, it was concluded that in order to conduct a successful waterflood, special measures had to be taken to insure that flood water should be injected into the sand only and to prevent its escape from the reservoir proper (Hunter, 1956). It was further concluded that old wells, which had been improperly cased and shot with nitroglycerine, could not be successfully recompleted as input wells. New input wells were drilled and they were cased to a point 5 to 10 feet below the top of the Burbank sand to seal off joints which might exist between the overlying silty shale and the sandstone reservoir. Existing wells in alternate east-west rows were plugged and the new input wells were drilled in the spaces between the old locations (Hunter, 1956). This created a 20 acre 5-spot pattern, but instead of a 5-spot square, it became a 5-spot rectangle also characterized as a "staggered line drive" (Muskat, 1938). Certain old wells in the line of input wells were not plugged and were retained for observation purposes. These wells quickly watered-out proving again the east-west channeling of input water (Hunter, 1956).

The 5-spot rectangle proved to be the most successful of any pattern used since the pilot flood which incidentally was a miniature version of the same pattern. The number of direct water channels were greatly reduced and flood production was greatly improved. The success of the 1954 development caused the operators to authorize a similar extension in 1956. This pattern was followed essentially for each of the successive extensions over the remainder of the field.

Can These Problems Be Avoided?

The obvious question is: could these problems have been avoided had the operators known about the extensive natural joint system? What can be done to predict such problems in the future?

In 1955, waterflood engineers reported:

> The deposits of Pennsylvanian age in the North Burbank field have evidently been extensively fractured throughout the section. Both the surface outcrops of Foraker Limestone and the underlying Cherokee Shale section have been vertically fractured. Evidence indicates that these vertical fractures are oriented primarily in an east-west direction.

The clue to the joint system in the reservoir is present on the surface in the form of densely jointed limestone outcrops. These very remarkable joints were recognized nearly 20 years before the North Burbank Unit waterflood program was started.

Early Recognition of Surface Joints

In August 1928, John L. Rich published the following "Geological Note" in the A.A.P.G. Bulletin: Jointing in Limestones as Seen From the Air.

> In the course of an airplane trip from Tulsa, Oklahoma to Wichita, Kansas by way of Bartlesville, * * * attention was irresistibly drawn to the geological features visible from the air. Most striking of these was the remarkable jointing displayed by certain limestones where they were exposed at the surface or under a thin cover of soil. About 6 miles north of Skiatook this feature was most clearly shown. Over an area of several square miles, a thin limestone, probably the Dewey member of the Drum Group, forms the capping of numerous isolated mesas, and is exposed in a wide outcrop on all projecting points. From a height of about 1,800 feet the entire joint pattern in this limestone could be seen with the greatest distinctness.

Figure 5 is an aerial photo of the area which Mr. Rich might have seen in 1928. The photo point is located 11 miles north of Skiatook and is actually the outcrop of the Avant Limestone. Rich continues:

> The joints are revealed by grass and other vegetation growing in the fissures. Where there appeared to be a considerable thickness of soil, the joint pattern could still be distinguished by lines of darker green in the vegetation along the joint planes. Though the details of the joint pattern differed in different places, it was noticed that the pattern generally consisted of two principal systems intersecting at approximately right angles. Directions, relative prominence of the two systems and spacing are variables. Other groups of joints making different angles with the principal systems were noticed here and there, the whole forming a network of the greatest beauty and interest.
>
> In flying over the route from Bartlesville to Wichita, the same features were noticed at many places wherever the limestone outcrops were wide. * * * The joints with their vegetation markers are so clear from the air that they could be photographed readily.
>
> Study of joint systems such as these from aerial photographs offers a field for interesting and, perhaps, important research on the relation of jointing to structure, * * * .

The following paragraphs give the details of a fracture analysis from aerial photographs of the Burbank area of Osage and Kay Counties, Oklahoma.

Fig. 5 - Stereo triplet showing joint patterns in Avant Limestone outcrop located 11 miles north of Skiatook, Oklahoma. This is possibly the area described in aerial view by Rich (1928). North is at the top of the page. Photo scale is roughly two inches equal to one mile. Using the stereoscope provided in the pocket, note the dominant east-northeast trending, systematic, Set I joints, and at right angles, the myriad non-systematic cross-joints. Longer north-northwest trending joints are Set II joints. Although the jointed rocks in the Burbank area are not as ideally exposed, the joint pattern here is the same and the viewer can readily appreciate how much detail is available to the photo interpreter. The dark toned beds which underlie the jointed Avant Limestone are shales, which are essentially devoid of joint traces. Several north-northwest trending faults of small displacement extend through the north-south elongate mesa at the north center of the photo.

NORTH

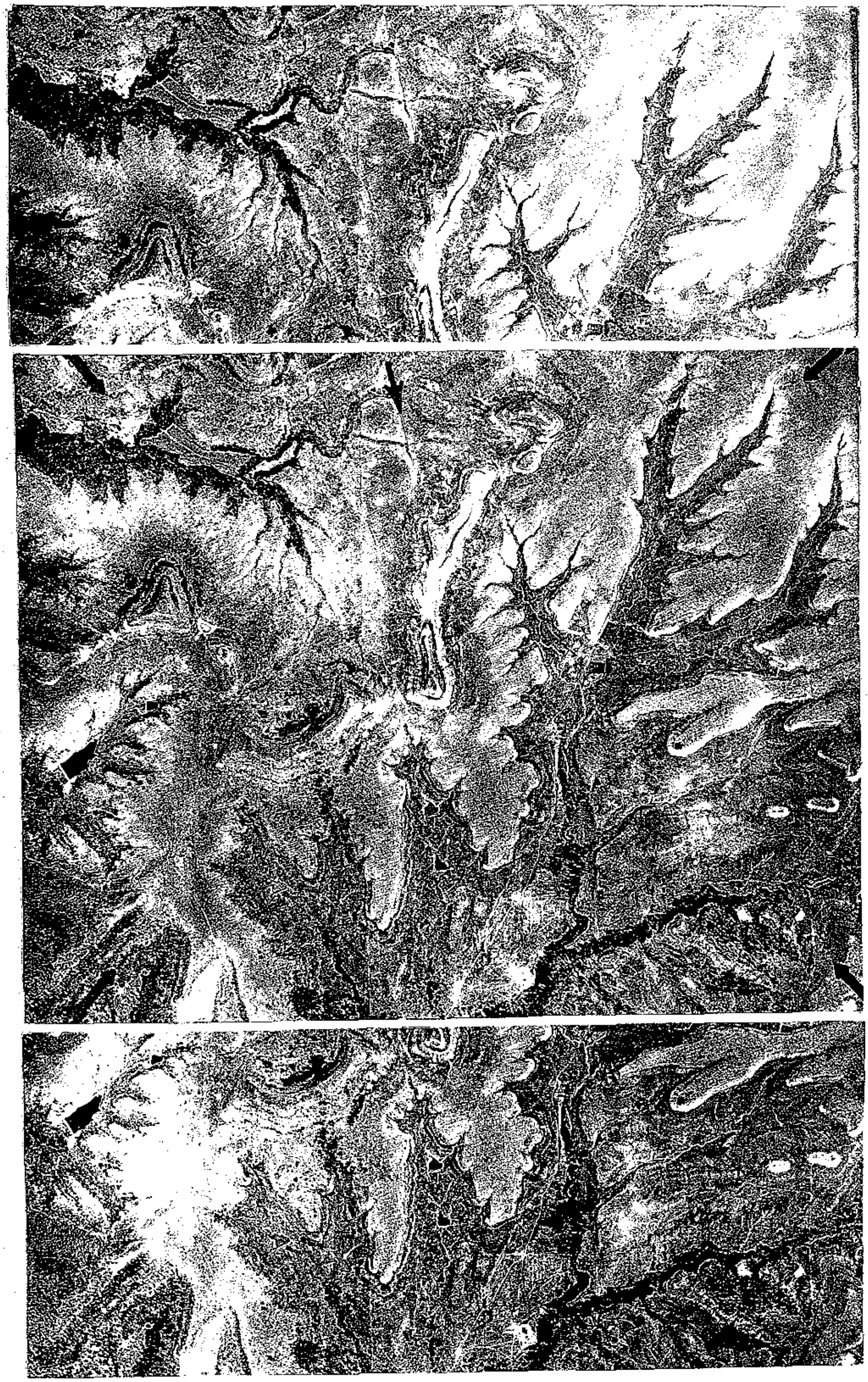


Fig. 5 - Stereo Triplet

JOINT ANALYSIS METHODS

Photomapping Methods

Details of the joint system were mapped on 18 stereo pairs of 1:15,000 scale, 18 x 18 inch aerial photographs using both mirror and lens type stereoscopes. The entire North Burbank area was carefully studied and individual joints annotated directly on the photo prints. Individual joints are visible to the eye on this large scale photography because they are enhanced by vegetation growing along the solution widened fissures, as aptly described in the quotation from Mr. Rich. Under the 2x magnification of the stereoscope, it was possible to delineate the true position, orientation, spacing, length and density of the myriad joints, as shown by the network of lines on Plate V. In some areas, the joint traces were too numerous to map even at this relatively large scale, and one line may represent several closely parallel joints.

Areal geology was mapped in detail on the aerial photos, in order to show the relationship of joint density to lithology of the outcrop exhibiting the joints. As expected, the greatest density occurs in the thicker competent limestone units. Conversely, the large areas devoid of joint traces are almost always underlain by shale.

Photomapping horizons do not always precisely coincide with formation boundaries. It is frequently necessary to trace a good resistant marker bed which may only approximate the true formation outcrop pattern. Photomapping horizons are shown on the columnar section included in the margin of Plate V.